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THIRTEEN NEW BL LACERTAE OBJECTS DISCOVERED BY AN EFFICIENT  
X-RAY/RADIO/OPTICAL TECHNIQUE<sup>1</sup>

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*Received:* ——— ; *Accepted:* ———

## ABSTRACT

We report the recent discovery of 13 serendipitous BL Lac objects in the *Einstein* IPC Slew Survey by means of X-ray/radio vs. X-ray/optical color-color diagrams and confirming optical spectroscopy. These 13 BL Lacs were discovered using a technique proposed by Stocke et al. (1989) which exploits the characteristic broad-band spectra of BL Lacs. New VLA detections provide accurate fluxes [ $f(6\text{ cm}) \sim 0.5\text{ mJy}$ ] and  $2''$  positions, facilitating the determination of an optical counterpart. All 13 new BL Lacs show essentially featureless optical spectra. Nine of these lie within the range of colors of known X-ray selected BL Lacs. Of the remaining four, one is apparently X-ray louder (by a factor of 1.5) or optically quieter (by 0.8 mags); and 3 are optically louder (by 1-1.3 mags) than X-ray selected BL Lacs. We expect  $\sim 50$  new BL Lacs in total, from our VLA work and upcoming Australia Telescope observations, yielding a complete Slew Survey sample of  $\sim 90$  BL Lacs.

*Subject Headings:* BL Lacertae objects: general — galaxies: nuclei — galaxies: X-rays — X-rays: sources — surveys

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## I. INTRODUCTION

BL Lac objects have been hard to find: in the 20 years following the discovery of the first example (Schmidt 1968), their numbers grew by only a factor  $\sim 10$  (Veron-Cetty and Veron 1991). By comparison, in the 20 years following the discovery of quasars (Schmidt 1963) their numbers grew 500-fold (Veron-Cetty and Veron 1991). Their elusiveness is due to the very lack of strong emission lines that make BL Lacs interesting. Even now less than 200 BL Lacs are known (Veron-Cetty and Veron 1991),  $\sim 2\%$  of known active objects. BL Lac objects account for  $\sim 2\%$  (162 out of 7765) of sources in the Veron-Cetty and Veron (1989) AGN catalog.

In the last few years, techniques using their distinguishing properties (Stocke et al. 1989) have made it possible to discover many new BL Lacs in the *Einstein* Extended Medium Survey (EMSS; Gioia et al. 1991; Stocke et al. 1991). This letter reports the extension of these efforts to the *Einstein* Slew Survey: we find 13 new BL Lac objects, which are the first results of a new, uniformly selected, sample of 85–90 bright BL Lacs.

## II. AN X-RAY/RADIO/OPTICAL TECHNIQUE FOR IDENTIFYING BL LACS

The key to finding BL Lacs is to exploit their salient characteristics:

First, all BL Lacs are radio loud [ $\alpha_{RO} > 0.3$ , i.e.  $f(6\text{ cm}) > 1\text{ mJy}$  for  $V \leq 20$ ; Stocke et al. 1991]. For this reason, radio surveys with follow-up optical spectroscopy (e.g., Kühr et al. 1981), have been considerably more efficient than optical surveys (6–8%).

Second, 98% of BL Lacs have distinctive X-ray/radio/optical colors (Stocke et al. 1991). Thus, X-ray surveys, combined with radio and optical data, have been shown to be the best approach to date ( $\sim 12\%$  efficiency; Stocke et al. 1991). The X-ray/radio/optical approach was highly successful in identifying 36 BL Lacs in the EMSS.

Third, the surface density of X-ray—selected BL Lacs flattens at fluxes below  $10^{-12}\text{ ergs s}^{-1}\text{ cm}^{-2}$  (Wolter et al. 1991). Therefore, wide-angle (all-sky) surveys are better for detecting BL Lacs than narrow-beam deep surveys. Because the EMSS covers only 2% of sky (up to  $\sim 5 \times 10^{-12}\text{ ergs s}^{-1}\text{ cm}^{-2}$ ), we need to use a shallow X-ray survey: the *Einstein* Slew Survey. The Slew Survey, constructed from 2799 individual slews of the IPC, covers 50% of sky at an exposure of 6 s (or, equivalently, to  $\sim 1 \times 10^{-9}\text{ ergs s}^{-1}\text{ cm}^{-2}$ ; Elvis et al. 1992). We estimate from the EMSS that a large number ( $\sim 50$ ) of new Slew BL Lacs will be identified, increasing the currently known number of BL Lacs by more than 30%.

Together these properties allow us to define a multi-step approach to identify BL Lacs, starting from the 193 unidentified Slew Survey sources:

1. Choose sources at high Galactic latitudes ( $|b| > 15^\circ$ ), with previous radio detections or a suggestive X-ray/radio flux upper limit;

2. Observe them with the VLA (hybrid CnB configuration, 2'' resolution, cf. 2' X-ray position), giving an accurate flux ( $\sim 0.5$  mJy);
3. Select point sources from the VLA maps as likely BL Lacs;
4. Use arcsecond VLA positions to find optical counterparts and magnitudes from digitized sky survey plates;
5. Place objects in the X-ray/radio/optical color-color diagram;
6. Obtain optical spectra of candidates with correct colors.

### III. CURRENT APPLICATION OF THE TECHNIQUE

The EMSS (Gioia et al. 1990) showed that the presence of a centimeter radio source of the proper flux within an X-ray error circle will yield a BL Lac object at  $\geq 80\%$  efficiency (Stocke et al. 1991). In Figure 1 (after Stocke et al. 1991), identified BL Lacs occupy a unique area in the radio/optical/X-ray (or  $\alpha_{OX}-\alpha_{RO}$ ) color-color diagram, compared to other extragalactic classes. The few ( $\leq 20\%$ ) non-BL Lacs in the region of Figure 1 bounded by  $\alpha_{RO} = (0.6, 0.3)$  and  $\alpha_{OX} = (1.2, 0.55)$  are either highly variable AGN or dominant galaxies in cooling-flow clusters, which are easily distinguished from BL Lacs with optical spectra.

Sources likely to be BL Lacs were selected primarily from the 193 unidentified Slew Survey sources, i.e. sources currently lacking proposed optical counterparts. As most of the unidentified sources are accessible from the North (76% with  $\delta > -40^\circ$ ), we obtained VLA observing time, as described below. Only 10% (19) of the targets had previous radio survey detections [ $f(6\text{ cm}) > 25$  mJy in Condon & Broderick 1985, 1987; or  $f(6\text{ cm}) > 60$  mJy in Condon and Broderick 1992]. We therefore prioritized sources as follows:

1. All high-latitude ( $|b| > 15^\circ$ ) unidentified sources (both radio detections and nondetections; see Table 1).
2. Slew sources with proposed optical counterparts of questionable validity, due to the lack of previous X-ray detections or confirming spectroscopy. These were all (a) stellar identifications, which are possible superpositions of foreground objects, or; (b) "normal" galaxy identifications, which may have active nuclei, or; (c) cluster identifications.
3. Unidentified sources at low latitudes, where a radio detection may indicate the presence of a pulsar.
4. Slew sources rejected from the source list because of a 10%–15% false-source rate and the requirement of high source reliability  $> 98\%$  (Elvis et al. 1992). In the 203 rejected unidentified sources, the false-source rate is slightly smaller (9%; from Figure 12 of Elvis et al.), but VLA detections would be highly significant.

In January, 1992, we observed a prioritized list of 152 Slew Survey sources at 6 cm with the VLA CnB hybrid configuration. The list contained 100 objects of Priority 1 (see above), 20 of Priority 2, 13 of Priority 3, and 19 of Priority 4. Using snapshot exposures of 3 minutes each, we achieved a  $5\sigma$  flux sensitivity of 0.5 mJy, and a positional accuracy of 2–3". The angular resolution clearly shows double-lobed, wide-angle-tail, or head-tail structure in many cases. Some 52 of the VLA detections identified with Slew sources (within the 80" 91% confidence radius of the Slew Survey) have the point-source radio morphology typical of BL Lac objects. Five of these have a second VLA point source within the Slew error box, where the ambiguity will be resolved using our color-color criteria once we have magnitudes for all sources. The 47 remaining BL Lac candidates are divided into 21 strong sources [ $f(6\text{cm}) > 10$  mJy], and 26 weaker sources [ $0.5 \text{ mJy} < f(6 \text{ cm}) \leq 10$  mJy].

To find optical magnitudes for the VLA sources, we are primarily using two  $B \sim 22$  digitized catalogs: in the South, the NRL catalog of objects derived from ROE scanning of the UK Schmidt plates; in the North, the Minnesota catalog derived from scanning the POSS plates. At this writing, the UK Schmidt plates (in the  $B_J$  band) are easier to work with, as NRL has all of the scanned UK Schmidt plates on EXABYTE tape. The U. Minnesota analysis is more time consuming, but provides both  $O$  and  $E$  band plate data, which is important for identifying optical counterparts to Slew Survey sources. In the case of either the POSS or the UK Schmidt digitized data, magnitudes are typically accurate to better than 0.5 mag, and positions to 0.5". These values are completely adequate for our analysis.

We obtained the magnitudes of optical counterparts in the VLA error circle. In no case has there been more than one possible counterpart, and we have found only one case without any possible counterparts, suggesting extreme optical variability (the Slew source 1ES1218+237). This is consistent with our expectation that the faintest expected Slew Survey objects will have  $B \sim 19$  (Schachter et al. 1992). Using star counts from the Galactic models of Bahcall & Soneira 1980, it is easy to show that even at the POSS or UK Schmidt plate flux limit of  $B \sim 22$ , and  $b = 20^\circ$ , the probability of a foreground source in the VLA error circle is small ( $\leq 5\%$ ).

Using optical magnitudes derived from digitized plate data, we can place 13 of the VLA sources in Figure 1. We scale POSS  $O$ -magnitudes and UK Schmidt  $B_J$ -magnitudes by +0.5 to obtain approximate  $V$  magnitudes, using the median ( $B - V$ ) of 0.5 in Veron-Cetty & Veron 1989. Bearing in mind the uncertainties in the IPC flux and  $V$  magnitude (shown graphically in Figure 1), 9 sources have the correct colors to be BL Lacs. These only require confirming spectroscopy for an absolute identification (see below). The remaining four sources have systematically smaller values of either  $\alpha_{OX}$  (1ES0347–121) or  $\alpha_{RO}$  (1ES0303+067, 1ES1440+122, 1ES1544+820) relative to EMSS BL Lacs.

The simplest explanation of the 4 outlier points is X-ray or optical flaring, which is plausible given the non-simultaneity of the X-ray, optical photometric, and radio observations, and the variability of BL Lacs at all known wavelengths (e.g., Schwartz et al. 19??). The low- $\alpha_{RO}$  sources 1ES0303+067, 1ES1440+122, and 1ES1544+820 could have flared optically while observed by the POSS by 1.3, 1.1, and 1.0 magnitudes and could still lie in the proper region of the diagram. Similarly, the low- $\alpha_{OX}$  source 1ES0347–121 could have been caught in a flaring X-ray state by the Slew Survey. A reduction in the observed Slew flux by a factor of 1.5 would give this sources the correct BL Lac colors. This value, which

cannot be attributed to uncertainty in determination of the Slew Survey flux (18%), is within the range of known BL Lac variability. Equivalently, 1ES0347-121 could have been fainter optically when observed in the sky survey plates by 0.8 mags and still have the correct colors. Finally, the third and most speculative explanation is that 1ES0347-121 is a prototype of a new class of X-ray loud BL Lac objects. In the mean, these would be a factor of  $\sim 4$  more X-ray loud than EMSS BL Lacs.

Optical spectra, beginning in June, 1991, were obtained by us at the Michigan/Dartmouth/MIT 1.3 m (R. R.), and the MMT (Blue Channel: J. P. H; Red Channel: J. L., J. T. S). No attempt was made at this stage to identify a complete sample; we simply aimed to identify as many sources favorable in each observing season as possible. For the 13 objects with correct colors (or discrepancies explainable by flaring), we obtained spectra, all of which turned out to be featureless.

Figure 2 shows spectra of the 13 confirmed BL Lac objects. The positions of these objects are also marked in the X-ray/radio/optical color-color diagram (Figure 1). Differences in signal-to-noise ratios result from different detectors and telescopes used in the observations. Despite these differences, it is clear that the spectra are uniformly featureless. Table 2 provides VLA positions, 6 cm fluxes, optical magnitudes and colors (if available), for the 13 confirmed BL Lacs. In addition, there are 4 more featureless spectra (not shown), which are VLA nondetections, but which have the correct colors to be BL Lacs in Figure 1 (based on Condon nondetections; §3b).

#### IV. DISCUSSION

The combined X-ray/radio/optical technique for identifying BL Lacs is evidently very efficient. There have been no cases in which a VLA point source in the BL Lac part of the  $\alpha_{RO}/\alpha_{OX}$  diagram has not turned to be in fact a BL Lac object, as defined by the featurelessness of its optical spectrum. The payoff is large, considering the small amount of observing time required per source (5 min snapshot at the VLA, then 10-20 min at an optical telescope).

We can compare the new 13 Slew Survey BL Lacs identified to date with the complete BL Lac sample of the EMSS, and the optically selected BL Lacs in Veron-Cetty and Veron (hereafter, VV; VV 19??). The median  $V$  magnitudes are 17.0 for VV, 19.1 for the EMSS, and 18.2 for the Slew Survey. This illustrates that we are filling in an important gap in presently known optically and X-ray-selected BL Lac samples. In units of  $10^{-12}$  ergs  $s^{-1}$   $cm^{-2}$ , the mean Slew Survey BL Lac X-ray flux is 2.6, compared to 1.5 for the EMSS. The Slew Survey BL Lacs are apparently  $\sim 2$ -2.5 times brighter than the EMSS BL Lacs, although (except for the two objects noted above) the X-ray-to-optical flux ratios between the two groups are consistent.

There are 38 more VLA point sources to be identified; using the EMSS as a guide, we eventually expect a yield of  $\sim 40$  BL Lacs from the 52 point sources detected at the VLA. Our observational program is accelerating. We have Australia Telescope time scheduled to pursue the deep southern ( $\delta < -40^\circ$ ) radio sources. Some 33 of these lie at high latitude.

Assuming a detection efficiency similar to our VLA work, we expect  $\sim 15$  AT detections, from which we will identify a dozen new BL Lacs. Hence, together with the 35 Slew Survey sources known from catalogs to be BL Lacs, and the complete VLA sample, we expect about 90 BL Lacs in the whole Slew Survey. Since they will be relatively bright and uniformly selected, they should prove valuable for both detailed follow-up observations of individual objects, and statistical population studies.

This work was supported by NASA grants NAG5-1746 (Slew Survey ADP), NAGW-2201 (Long Term Space Astrophysics), and NAS8-3751 (*Einstein* Data Center) to SAO; and by NASA grant NAGW-2645 and NSF grant AST-9020008 to the University of Colorado.

Table 1: VLA Observations of BL Lac Candidates

Source Group	Number Unidentified	Number Observed at VLA (Pct.)
Slew Survey <sup>a</sup>	193	113 (59%)
Northern ( $\delta > -40^\circ$ )	147	113 (77%)
High Latitude ( $ b  > 15^\circ$ )	111	100 (90%)
Low Latitude	36	13 (36%)
Southern	46	0 <sup>b</sup>

a. From source list of 809 objects.

b. Southern sources will be observed at the Australia Telescope in July, 1992.

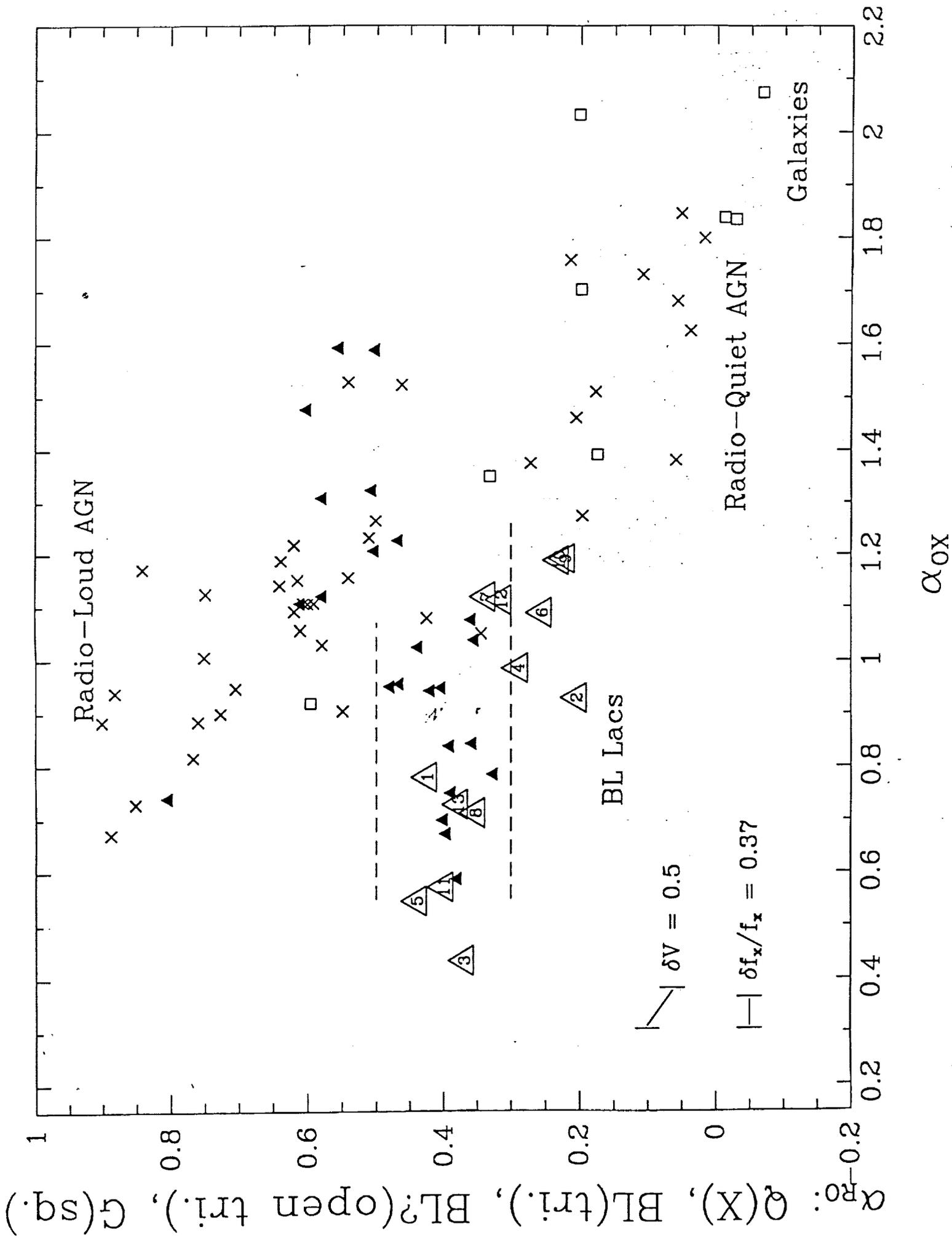
Table 2: New BL Lac Identifications

Index	Name	Posn. J2000	RA Off. (")	DEC Off. (")	f(6 cm) (mJy)	$m_O$ (mags)	$m_O - m_E$ (mags)	Spec. Note <sup>a</sup>
1	1ES0229+200	02 32 48.6 +20 17 17	+25	-12	41.5	18.0	4.7	Luu/Rem.
2	1ES0303+067	03 06 09.7 +05 58 28	+71	-116	3.9	17.6:	...	Rem.
3	1ES0347-121	03 49 23.2 -11 59 27	+3	-1	7.6	19.1(J)	...	Rem.
4	1ES0502+675 <sup>b</sup>	05 07 56.2 +67 37 24	-4	-1	31.3	16.5:	...	Sto./Rem.
5	1ES0525+713 <sup>c</sup>	05 31 41.7 +71 22 17	+3	+68	8.6	19.9:	...	Rem.
6	1ES0647+250	06 50 46.5 +25 03 00	-11	+11	61.0	15.3:	...	Rem.
7	1ES0806+524 <sup>b</sup>	08 09 49.2 +52 18 58	0	+3	169	15.3	1.8	Sto.
8	1ES1028+511	10 31 18.5 +50 53 36	-1	+1	42.5	17.0	0.7	Sto.
9	1ES1440+122	14 42 48.3 +12 00 40	-9	-1	40.2	15.3:	...	Sto.
10	1ES1544+820	15 40 15.7 +81 55 06	+2	+3	45.1	15.3:	...	Sto.
11	1ES1927+654	19 28 19.5 +65 33 55	+13	-3	16.0	18.7:	...	Rem.
12	1ES1959+650	19 59 59.9 +65 08 55	-5	+14	241.0	14.6:	...	Sto./Rem.
13	1ES2343-151	23 45 38.4 -14 49 29	+16	-11	7.7	19.2(J)	...	Huch.

a. Notes on spectra: *Huch.*—J. Huchra, MMT Blue Channel, *Luu*—J. Luu, MMT Red Channel, *Rem.*—R. Remillard, MDM 1.3 m, *Sto.*—J. Stocke, MMT Red Channel.

b. Priority 4 source; see §3.

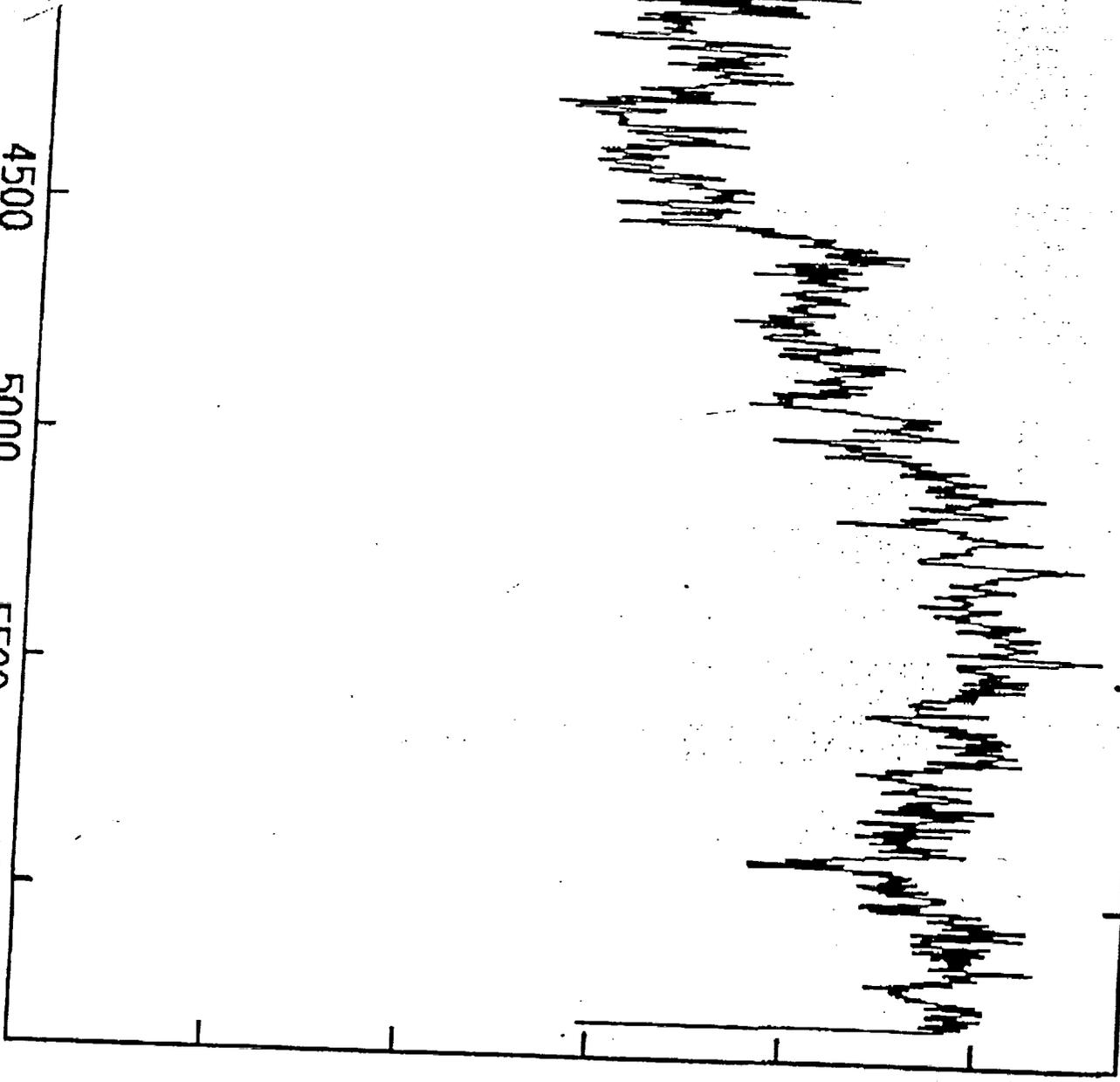
c. Possible wide-angle-tail source.



## FIGURE CAPTIONS

Figure 1: Color-Color diagram for the 13 new BL Lac objects reported in this paper (open triangles; numbered as in Table 2), compared with identified Slew Survey AGN ( $x$ 's), BL Lacs (closed triangles), and normal galaxies (squares) known from positional coincidences in optical catalogs. Definitions of the quantities  $\alpha_{OX}$  and  $\alpha_{RO}$  are taken from Stocke et al. 1991. Changes in the spectral indices expected from typical uncertainties in  $V$ -magnitude and relative IPC flux are shown.

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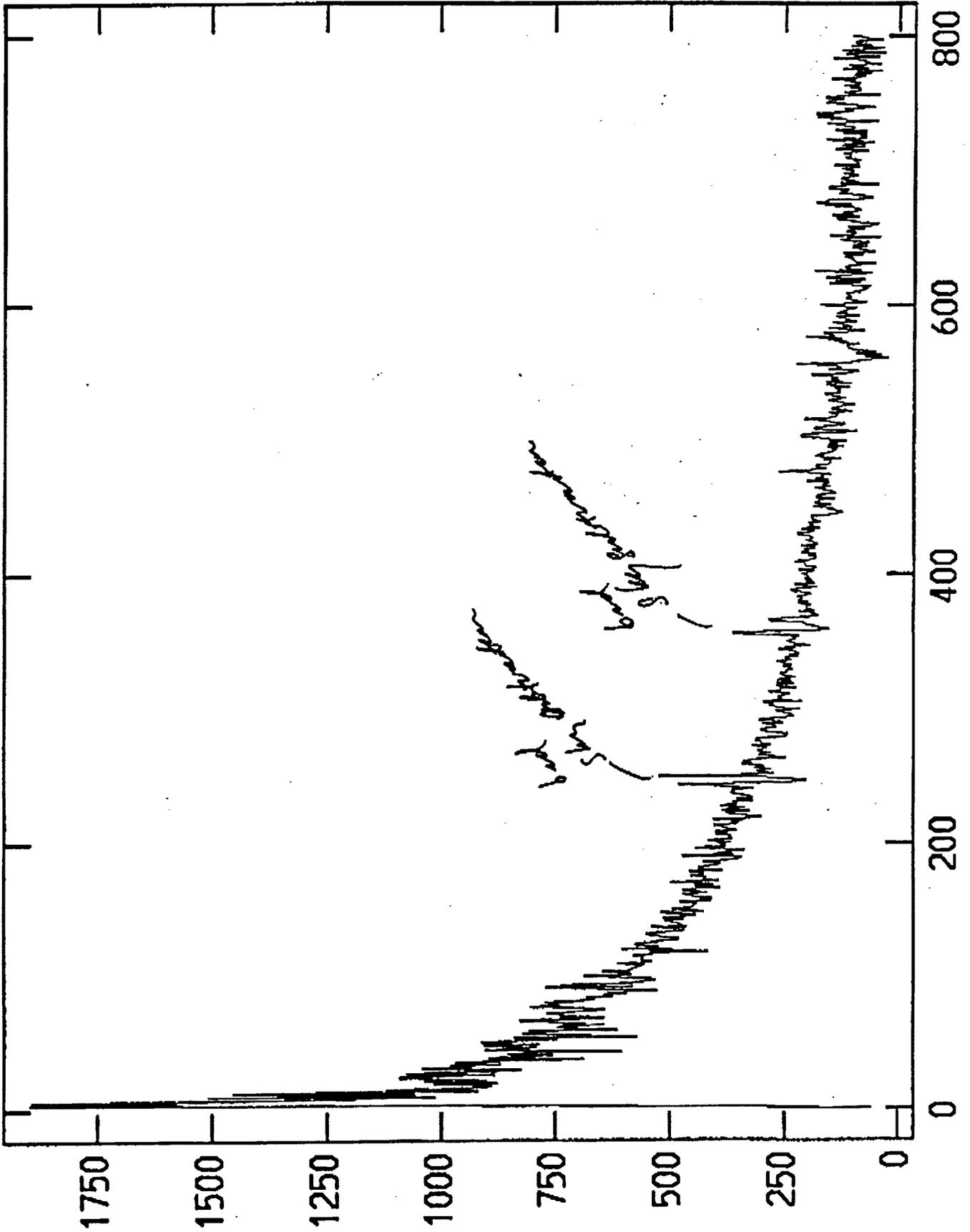
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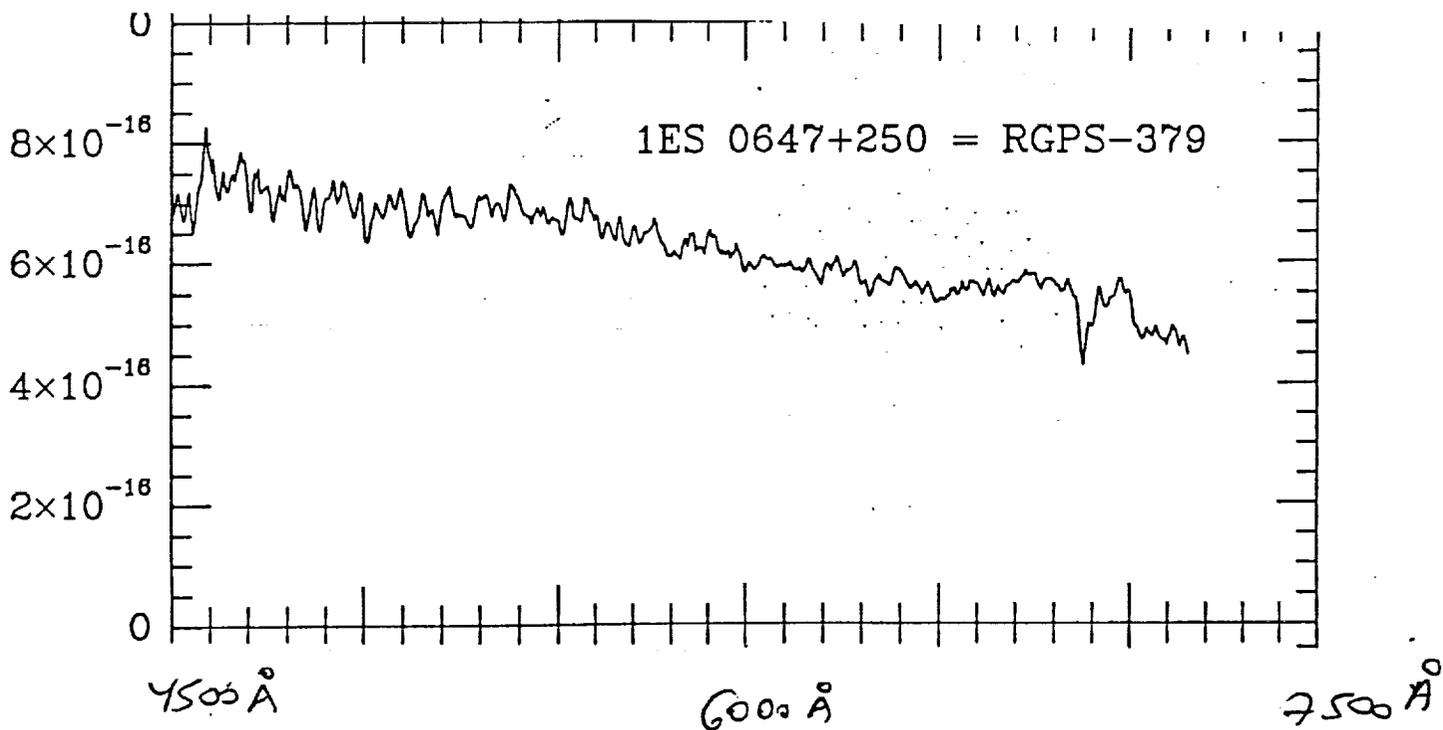
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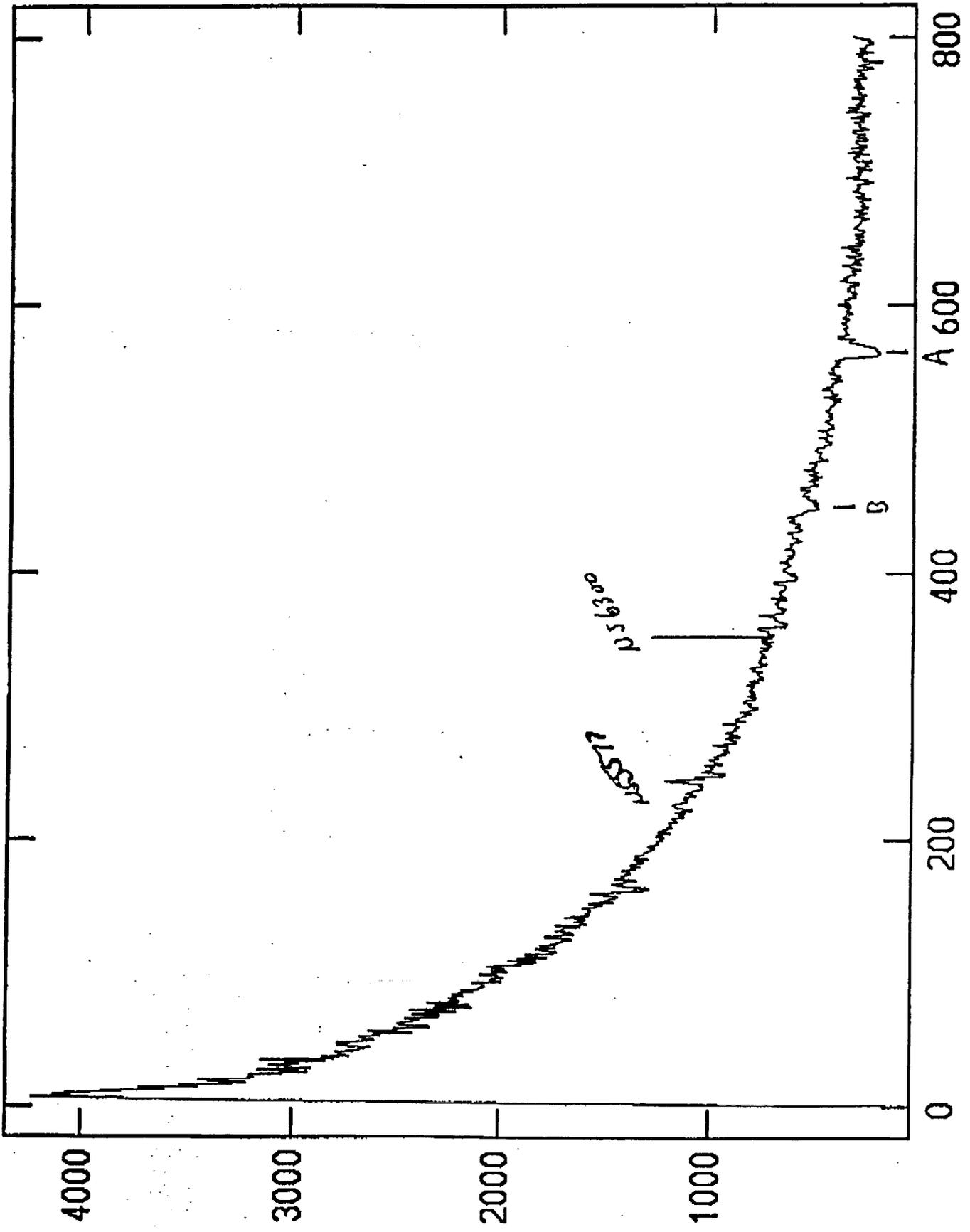
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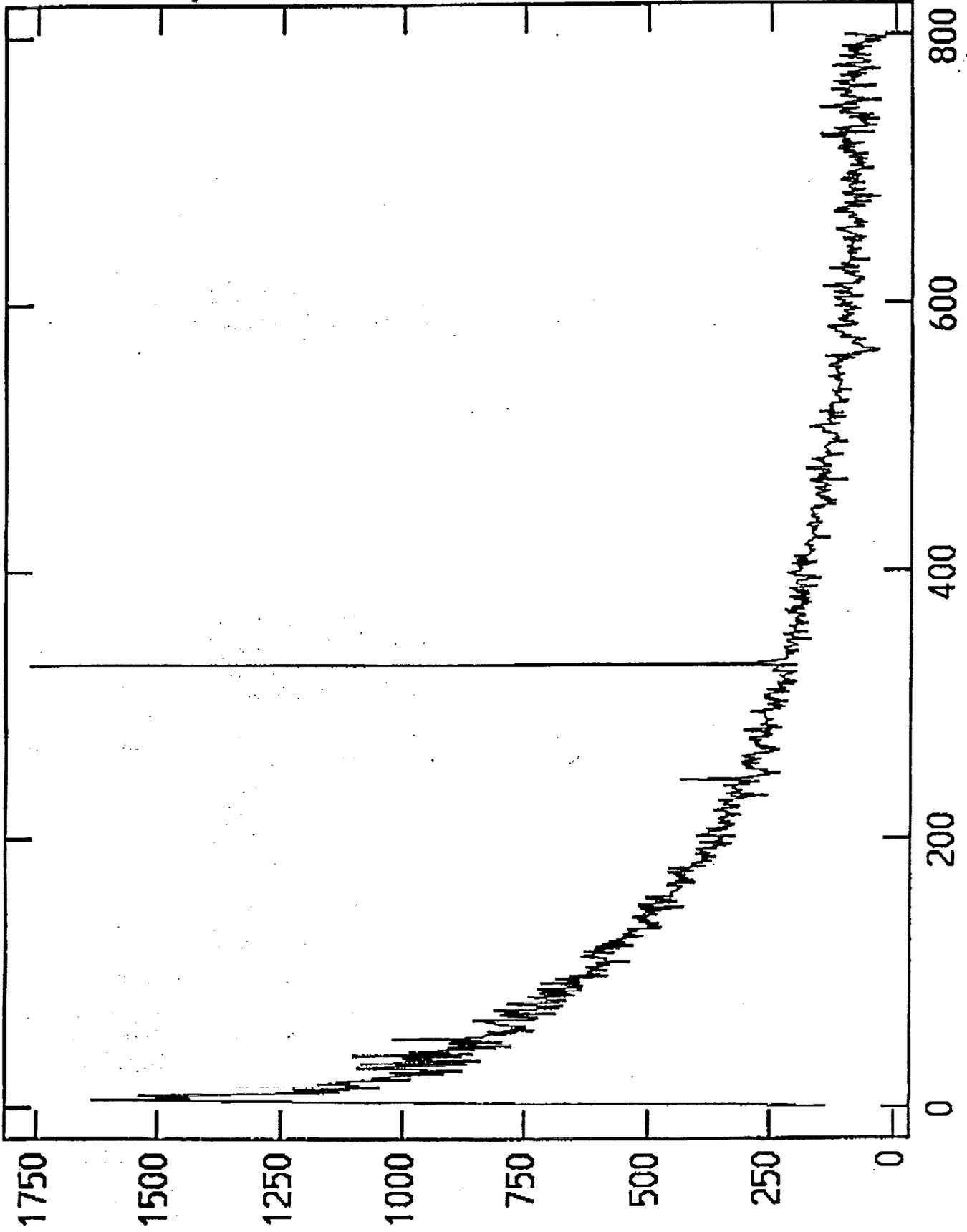
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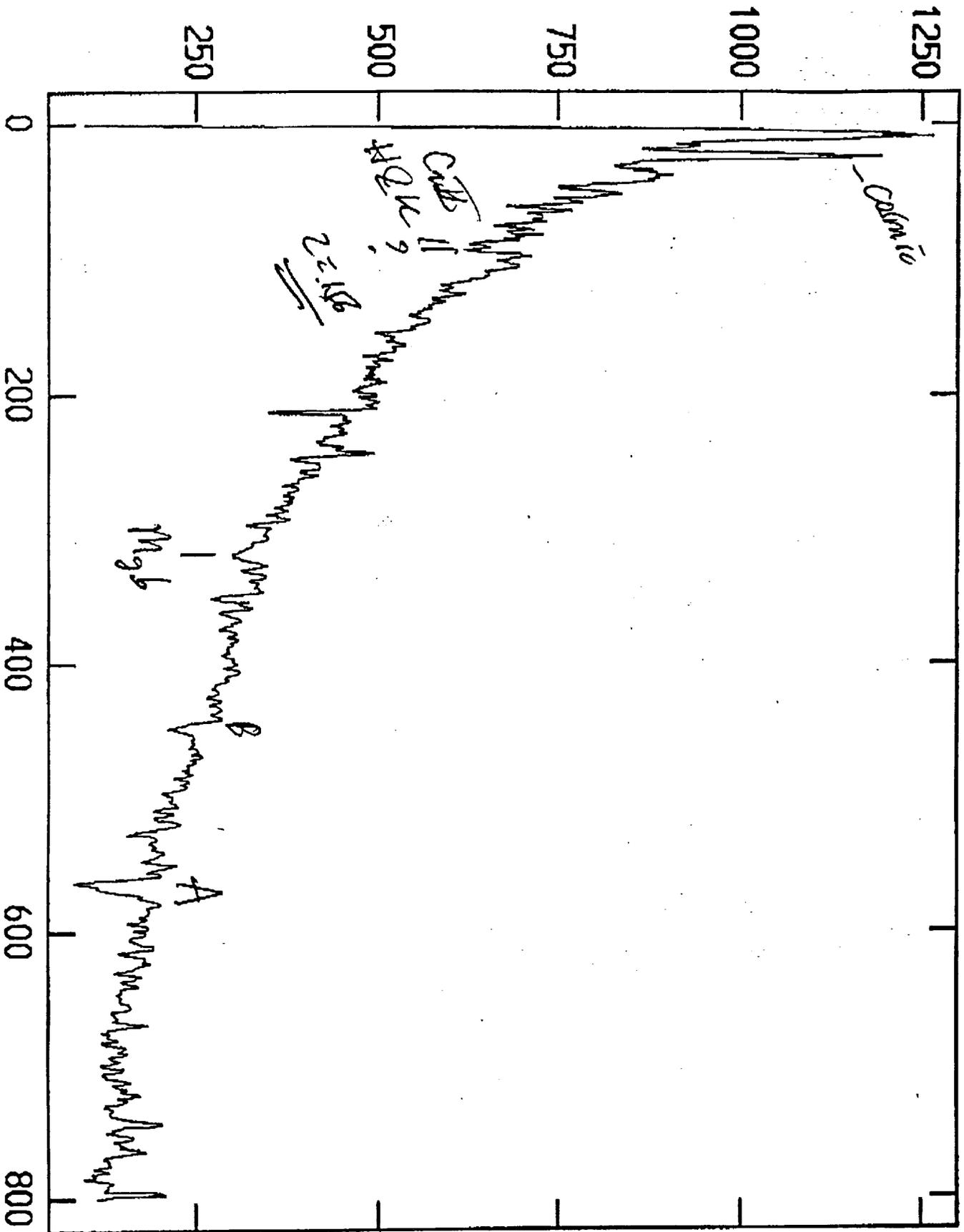
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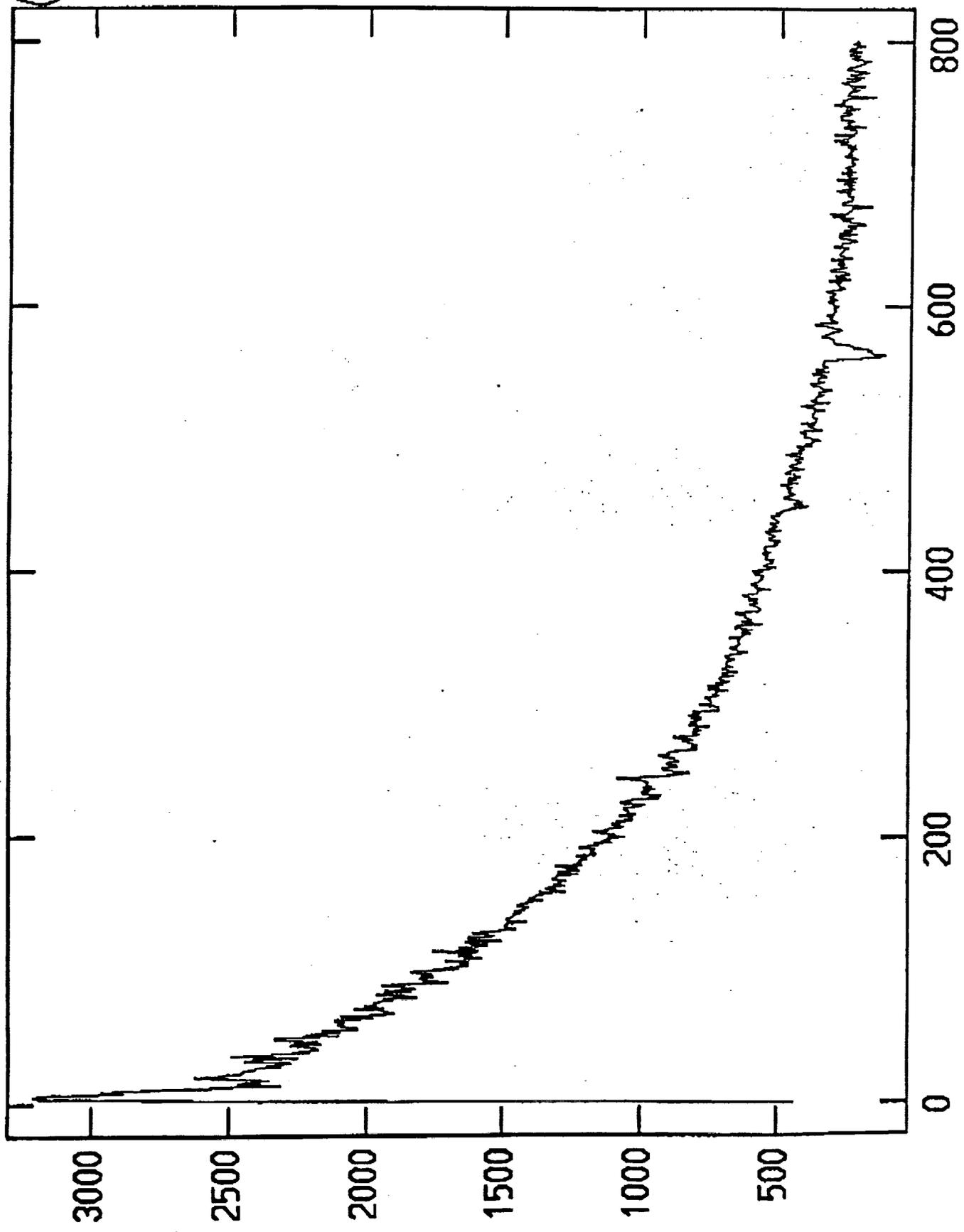
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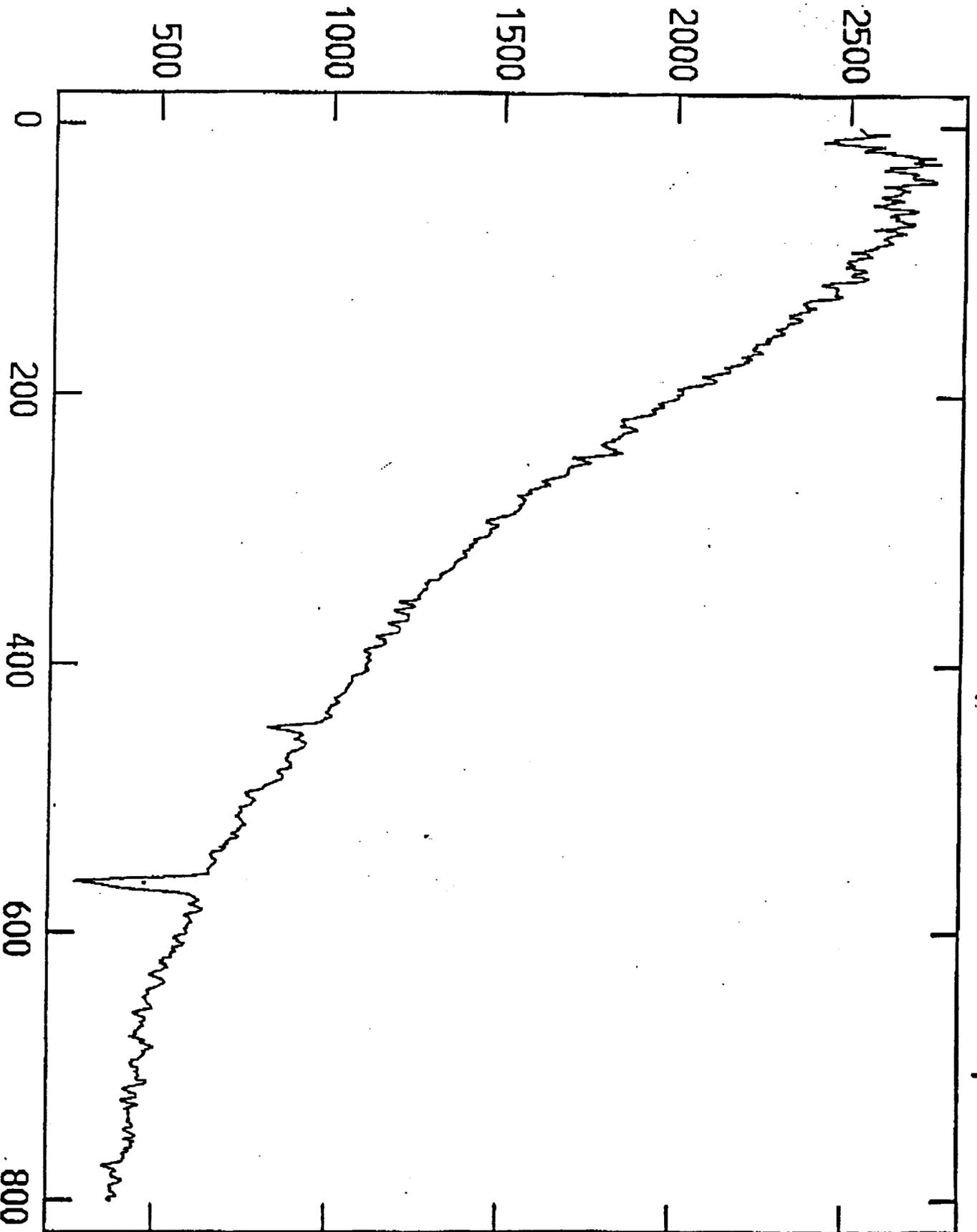
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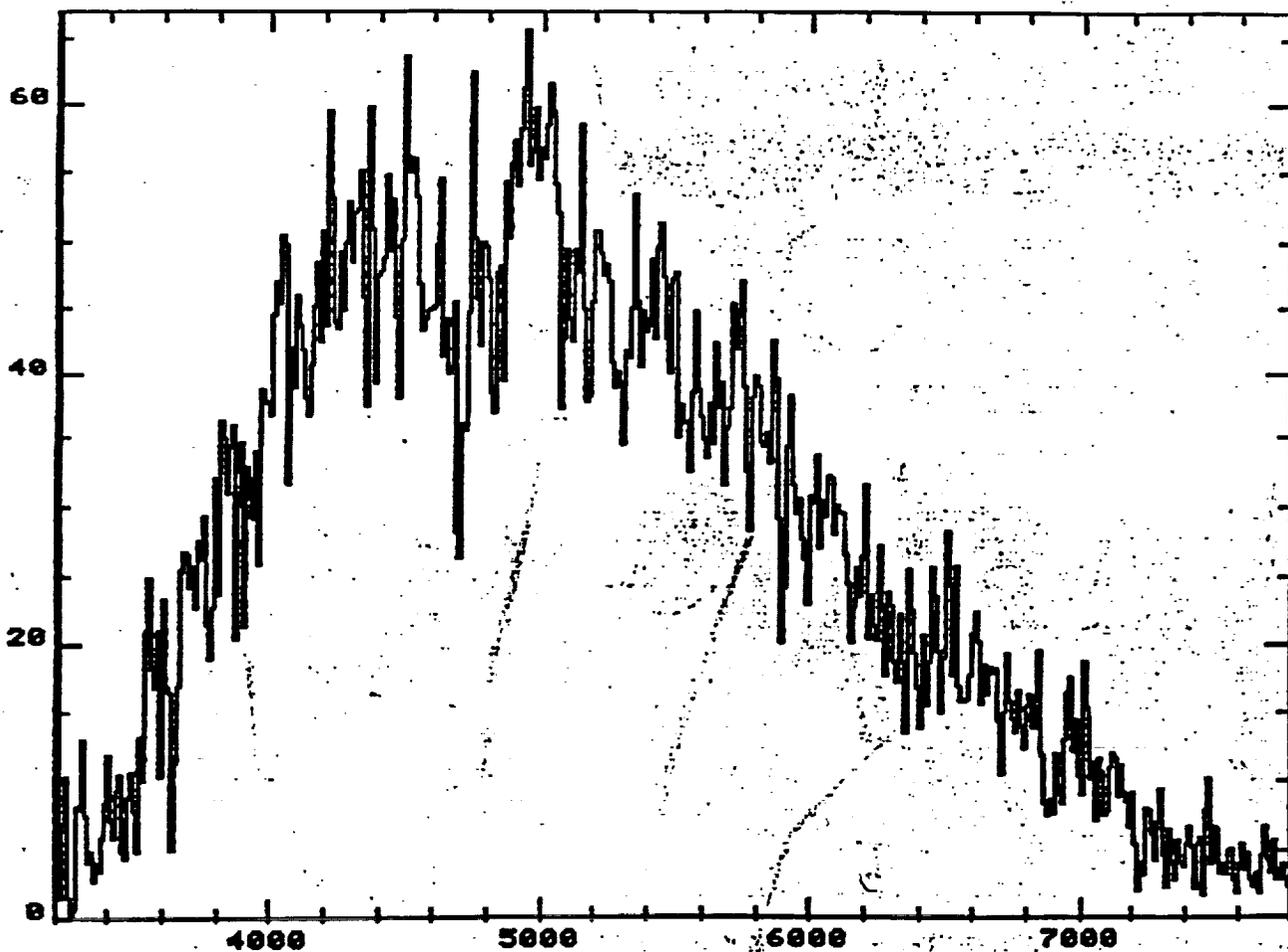
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